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Impact of climate and demographic changes on the vegetation of the M'goun Geopark UNESCO of Morocco (1984-2021)

Impacto de los cambios climáticos y demográficos en la vegetación del Geoparque M'goun de la UNESCO en Marruecos (1984-2021)

AUTHORSHIP

Gharnit Youssef
Environmental, Ecological and Agroindustrial Engineering Laboratory, University Sultan Moulay Slimane, Faculty of Science and Technology, Beni Mellal, Morocco.

Moujane Abdelaziz
Environmental, Ecological and Agroindustrial Engineering Laboratory, University Sultan Moulay Slimane, Faculty of Science and Technology, Beni Mellal, Morocco.

Outourakht Aboubakre
Environmental, Ecological and Agroindustrial Engineering Laboratory, University Sultan Moulay Slimane, Faculty of Science and Technology, Beni Mellal, Morocco.

Aziz Hasib
Environmental, Ecological and Agroindustrial Engineering Laboratory, University Sultan Moulay Slimane, Faculty of Science and Technology, Beni Mellal, Morocco.

Abdelali Boulli
Environmental, Ecological and Agroindustrial Engineering Laboratory, University Sultan Moulay Slimane, Faculty of Science and Technology, Beni Mellal, Morocco.

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CORRESPONDENCE
Gharnit Youssef (gharnityoussef@gmail.com)

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Abstract

The primary goal of this study is to identify changes in the vegetation cover of the geopark M'goun region of Morocco, as a sample area to track the Moroccan vegetation status, and the crucial factors that influenced its evolution between 1984 and 2021. The NDVI (Normalized Difference Vegetation Index) method has been used, combined with supervised classification manipulated with the Google Earth Engine and through statistical analysis using R, together with field trips and Google Earth records for supervised classification. The percentage of vegetation density, made up of oak groves, Matorrals, red juniper, and thuja, in addition to a highly biodiverse cover, displays a declining trend. Medium-cover vegetation decreased by 29.5%, dense vegetation decreased considerably by 70.9%, and low-cover vegetation saw a minimal decline of 0.02%. As a result, dense and medium vegetation are being replaced by bare lands or poor-quality cover formed by sparse plants and solitary trees. In addition, precipitation increased slightly, showing an irregular trend, with average minimum and maximum temperatures rising by +1.7°C and +1.4°C, respectively. Furthermore, the population increased by 84.47%. Statistical analysis showed that the most important parameters affecting medium and dense vegetation cover are temperatures (Tmin and Tmax) and population density, as evidenced by the strong correlation between them. In contrast, sparse vegetation cover showed less correlation due to its heterogeneity. However, precipitation played a minimal role in vegetation evolution. Change detection maps revealed a significant negative impact on vegetation cover. This degradation was localized in the southern part of the area of study, where, according to the demographic density map, the majority of the population resides. Deforestation continues due to the lifestyle and economic activities of the local population. These factors, combined with climate change, are exerting large-scale pressure on the forest throughout the geopark.

Keywords: vegetation cover; change detection; climate change; population; NDVI; supervised classification.

Resumen

El objetivo principal de este estudio es identificar los cambios en la cobertura vegetal de la región del geoparque M'goun en Marruecos, como área de muestra para monitorear el estado de la vegetación marroquí, y los factores cruciales que influyen en su evolución entre 1984 y 2021.

Se utilizó el método del Índice de Vegetación de Diferencia Normalizada (NDVI, por sus siglas en inglés), combinado con clasificación supervisada manipulada mediante Google Earth Engine y análisis estadístico utilizando R, junto con visitas de campo y registros de Google Earth para la clasificación supervisada. El porcentaje de densidad de vegetación, que incluye bosques de roble, matorrales, enebro rojo y tuya, junto con una cubierta altamente biodiversa, tiende a disminuir. La vegetación de cobertura media disminuyó en un 29,5%, la vegetación densa disminuyó considerablemente en un 70,9% y la vegetación de cobertura baja experimentó una disminución mínima del 0,02%. Como resultado, la vegetación densa y de cobertura media está siendo reemplazada por tierras desnudas o coberturas de mala calidad formadas por plantas dispersas y árboles solitarios. Además, las precipitaciones aumentaron ligeramente y tendieron a ser irregulares, con un aumento promedio de las temperaturas mínimas y máximas de +1,7 °C y +1,4 °C, respectivamente. Además, la población aumentó en un 84,47%. El análisis estadístico mostró que los parámetros más importantes que afectan la cobertura de vegetación de cobertura media y densa son las temperaturas (Tmin y Tmax) y la densidad de población, como se evidencia por la fuerte correlación entre ellos. En contraste, la cobertura vegetal dispersa mostró una menor correlación debido a su heterogeneidad. Sin embargo, las precipitaciones jugaron un papel mínimo en la evolución de la vegetación. El mapa de detección de cambios reveló un impacto negativo significativo en la cobertura vegetal. Esta degradación se localizó en la parte sur del área estudiada, donde, según el mapa de densidad demográfica, reside la mayoría de la población. La deforestación continúa debido al estilo de vida y las actividades económicas de la población local. Estos factores, combinados con el cambio climático, están ejerciendo una presión a gran escala sobre el bosque en todo el geoparque.

Palabras clave: cobertura vegetal; detección de cambios; cambio climático; población; NDVI; clasificación supervisada.

1. Introduction

The Mediterranean is recognized as a global biodiversity hotspot (Myers et al., 2000). In addition, Mediterranean countries had an estimated forested area exceeding 85 million hectares (ha) in 2010, representing 2 percent of the world's total forested area (Berrahmouni & Christophe, 2013). However, the Mediterranean region is highly susceptible to a multitude of pressures and threats (Noce & Santini, 2018) ; especially human activities, such as logging, grazing, urbanization, forest fires, and agriculture, have altered the woodlands, resulting in areas of sparse woody vegetation known as maquis and garrigue (Valbuena & Pelayo, 2014), and these forests have also been impacted by excessive logging, fire, and overgrazing by livestock, particularly goats, leading to a significant degradation of their natural characteristics (Nias & Mooney, 2007). Furthermore, climate change scenarios predict massive impacts on Mediterranean forests (Solomou et al., 2017).

As a part of the Mediterranean region and situated in an arid and semi-arid climatic zone, the Moroccan ecosystems have encountered numerous challenges. Forests and woodland ecosystems in Morocco have a vital role in preserving biodiversity and supplying ecological and economic benefits (Serbouti et al., 2023), such as providing habitat for millions plants and animals (Eyvindson et al., 2018), and combat against the desertification (Benzyane, 2007). Moreover, the forestry industry in Morocco has played a significant role in the country's economy, making the largest economic contribution (African Developemnt Bank, 2000), as the quantity of wood extracted from the Moroccan forest reaches 10 million m^3/year (Benzyane, 2007; Hammouyat et al., 2022) . In addition, Forest areas in Morocco cover 9 million hectares, which accounts for 12% of the national territory (Laaribya et al., 2017), This wealth is due to the uniqueness from a geographic, climatic, and ecological perspective (Berrahmouni & Christophe, 2013), the most representative forests in Morocco *are Tetraclinis articulata* forest with an area of 450,000 ha, *Argania spinosa* 450,000 ha, *Quercus rotundifolia* 400,000 ha and *Quercus suber* 400,000 ha (des Eaux & du Maroc, 1927). Nevertheless, the Moroccan forest, a significant economic and ecological heritage, continues to remain relatively unknown, and it is presently facing threats resulting from ongoing genetic deterioration (Narjisse et al., 2001) besides the desertification (Boubekraoui et al., 2023) and climate changes (Ilmen & Benjelloun, 2013) among others. Furthermore, the 13 million hectares of arid, semi-arid, and sub-humid rangelands in Morocco, 4.6 million hectares are highly degraded, and an additional 5.3 million hectares are considered moderately degraded (General Company of Technical and Economic Studies of Morocco [SOGETEG], 1983). Morocco's land use can be summarized as 5.8 million hectares of forests (8%), 9.2 million ha of agricultural lands (13%) and 46 million ha of pastures, rangelands and deserts (Dahan et al., 2013).

Several techniques are used to study and monitor vegetation resources, especially remote sensing (Karhale, 2021; Rogan & Chen, 2004; Shandilya et al., 2007), among other remote sensing satellite contributions, Landsat is widely used (Ait El Haj et al., 2023; Cai et al., 2020; Dhaloiya et al., 2023; Milanović et al., 2019) by application of NDVI index (Ozyavuz, et al., 2015; Sonali et al., 2021) and supervised classification (Bispo et al., 2013; Salata, 2021). A study in Benslimane, nearby area, is carried out by Hammouyat et al., using the same process, revealed that the forest is declined by 11.4 % losing nearly 200 ha/year (Hammouyat et al., 2022), and Houssni et al. (2018) showed that high formations, low formations, and matorrals have regressed by 62%, 70%, and 49% respectively in the Western Rif region of Morocco (Houssni et al., 2018).

Therefore, to monitor and analyze changes in the forests of the Moroccan Atlas region, the M'goun geopark, a protected area with unique features, has been selected as an example. This assessment aims to determine the extent of vegetation cover and identify the variables and threats that have influenced its changes over time, particularly in relation to climate and population changes. Remote sensing, specifically Landsat satellite data, is utilized to track the areas covered by different vegetation classes between 1984 and 2021, using two remote sensing techniques, the NDVI index and supervised classification techniques. Additionally, change detection techniques are used to locate the affected zones and compare them with demographic density fluctuations.

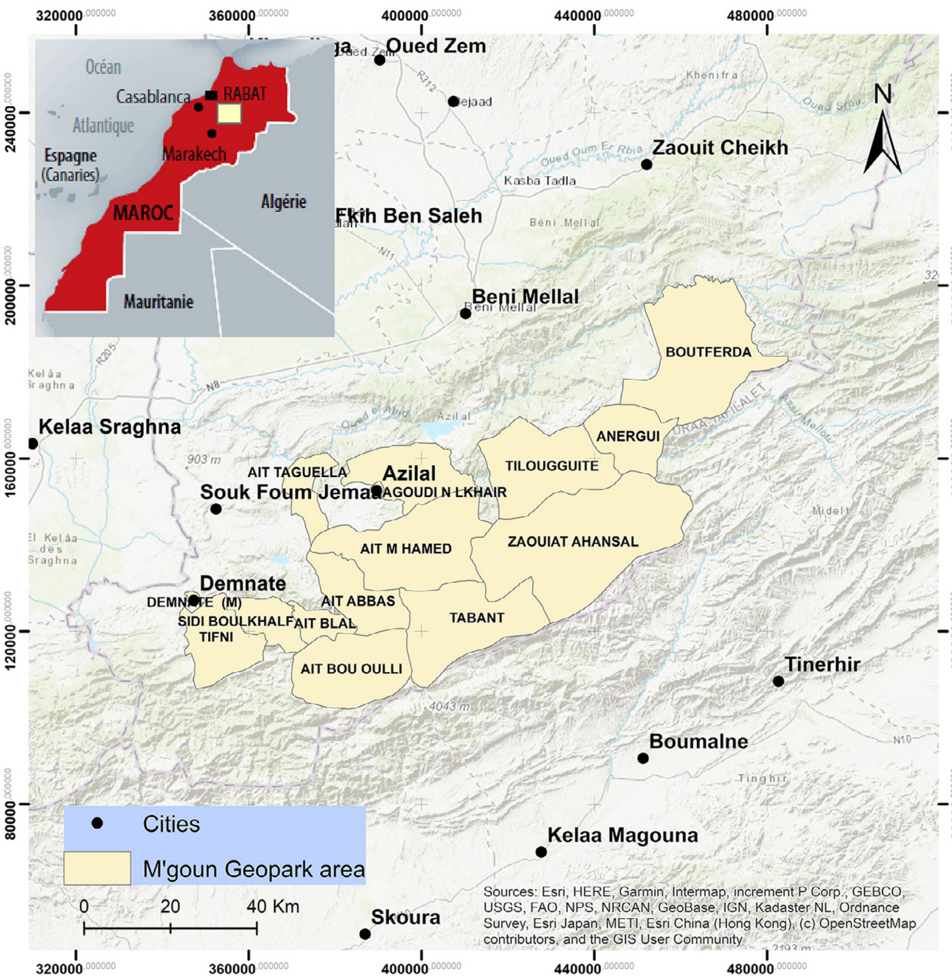
2. Methodology

2.1. Study area

The Geopark is located in the central part of Morocco (Figure 1), specifically in the Azilal province, covering an area of 9,800 km^2. It is part of the Central High Atlas region. The geopark has been recognized by UNESCO in 2014 as an international heritage site, encompassing an area of 5,700 km^2.

The entire M'goun UNESCO geopark area is characterized by mountainous terrain, with elevations ranging from 539 m to 3,695 m. The average altitude is 1,588 m, and the terrain becomes more rugged towards the south.

Figure 1. The geographic location of the study area



Own elaboration

The region's mountainous and Atlas-like terrain has a significant influence on its climate, which is typically characterized as semi-arid and Mediterranean (Taïbi et al., 2019), the winter season is cold and rainy, while the summer season is hot and dry (Ionesco, et al., 1966). The climate becomes more continental towards the high mountains, as indicated by the regional direction of Meteorology (Direction Régionale, 2010), rainfall in the region is variable and seasonal, with low-lying areas experiencing rain showers and higher altitudes receiving significant snowfall during the cold season, which may persist until July in areas such as the Azourki ranges. The average precipitation in the region ranges from 500 mm to 700 mm, with snow precipitation accounting for 20% to 30% (Taïbi et al., 2019). Temperature fluctuations are significant, with high mountains experiencing negative values during winter and temperatures exceeding 40 degrees Celsius in summer (NASA, 2021). Moreover, the region is characterized by significant soil complexity, with a variety of magmatic rocks, red siltites, evaporites, and basalts underlain by limestone formations, marl, and clayey sandstone (Gharnit et al., 2023).

The main vegetation habitats in the geopark are holm oak groves (*Quercus ilex* L.), red juniper (*Juniperus phoenicea* L.), thuja (*Tetraclinis articulata* (Vahl) Mast.), Aleppo pine (*Pinus halepensis* Mill.), and high-altitude cushions (xerophytes with *Juniperus thurifera* L.). At low altitudes of the geopark, ranging from 800 to 1,400m, *Tetraclinis articulata* (Vahl) Mast. is accompanied by a diverse cover, including *Ceratonia siliqua* L., *Pistacia lentiscus* L., *Olea europaea* L., *Euphorbia resinifera* O. Berg, *Phylirea* sp., *Cistus crispus* L., *Cistus albidus* L., *Marrubium vulgare* L., and others. As elevations increase, *Juniperus phoenicea* L. gradually replaces *Tetraclinis articulata* (Vahl) Mast., often coexisting with the same species but with differences in abundance. *Pinus halepensis* appears from 1,200m and reaches 1,800m, forming a habitat with significant species richness, including *Thymus satureioides* Coss. ex Batt. & Trab., *Globularia alypum* L., *Lavandula* sp., and others. Holm oak appears from 1,100m to 2,400m, and this habitat undergoes pronounced changes. *Quercus ilex* has an exceptional understory with species such as *Juniperus oxycedrus* L., *Chamaerops humilis* L., *Crataegus azarolus* L., *Buxus balearica* Lam., *Arbutus unedo* L., and more. At high elevations, from 1,900m to 2,500m, Juniperus thurifera becomes the main species, accompanied by xerophytes like *Ormenis scariosa* (L.) Dostál, *Zylla spinosa* (L.) Pruski, *Bupleurum spinosum* L., *Astragalus* sp., *Cytisus balansae* Boiss., and others.

2.2. NDVI (Normalized Difference Vegetal Index)

NDVI, known as the Normalized Difference Vegetation Index, is a widely used vegetation index among many others (Tucker, 1979). It generates values between -1 and 1, which reflect the density of vegetation cover (Roussillon, 2016). Areas with bare rock surfaces, sand, and snow typically have low NDVI values, usually less than 0.1. Sparse vegetation such as grasses, meadows, and senescent crops typically have moderate NDVI values, ranging from approximately 0.2 to 0.5. Large NDVI values (>0.6) correspond to dense vegetation, as commonly observed in areas with dense forest or vegetation cover (United States Geological Survey [USGS], 2022).

$$NDVI = \frac{NIR - R}{NIR + R}$$

NIR: the reflectance at the near infrared spectrum.
R: reflectance at the red spectrum.

2.3. Supervised classification

Remotely sensed imagery identifying as the best type of data has information throughout the world (Abbas & Sabah, 2020), Classification of satellite images is an important key for ground features extraction and thematic maps production (Shwaky et al., 2018). Very common task in remote sensing applications is image classification, whose most common products include land cover maps, assessment of deforestation, burned forest areas, crop acreage, production estimation and pollution monitoring (Samaniego et al., 2008; Zhu & Basir, 2005) Supervised classification techniques are algorithms that 'learn' patterns in data to predict an associated discrete class (Stephens & Diesing, 2014). There are several classification techniques; such as maximum likelihood classification, minimum distance classification, parallelepiped classification (Richards, 1986). Maximum likelihood classification (MLC) is most widely used supervised classification and used in a variety of applications (Sisodia et al., 2014), Therefore this technique is used to perform the supervised classification.

2.4. Change detection

"Change detection" is a process that involves identifying differences in the states of an object or phenomenon (Mohamed & Mobarak, 2016). It is a method used to describe changes observed at the level of land use

(Meera Gandhi et al., 2015). In this study, the change detection method has been utilized, which involves subtracting the vegetation density map (NDVI) of the year 2021 from the year 1984 to determine, through value analysis, the areas where vegetation has flourished and the areas where it has degraded.

Locations where the vegetation has deteriorated, resulting in a decrease in density or pixel value in 2021 compared to 1984, are expected to return negative values. Sites with little or no change are expected to have values close to or equal to 0, indicating little or no difference between the two years. Positive values are expected for locations where the vegetation cover has increased, indicating positive changes in NDVI values (values are higher in 2021 compared to 1984).

2.5. Climate data

Regarding the climate data, four stations covering all the study area surface and elevation ranges have been selected; Demnate at 960 m above sea level (a.s.l), Azilal at 1,377 m, Zaouit Ahensal at 1,700 m, and Boutferda at 2,400 m. Then the mean values of each parameter, including maximal and minimal temperatures (Tmax and Tmin) and precipitation, were calculated. This data was extracted from The Climate Toolbox, a climate program developed through collaboration between CIRC (Climate impact Research consortium), USDA (United States Department of Agriculture), University of California, Northwest Climate Adaptation Science Center and others (see https://climatetoolbox.org/). Moreover, the Worldclim data is used to create the spatial variation of climatic variables (see https://www.worldclim.org).

2.6. Demographic data

Based on the results of the census carried out by The High Commission for Planning (https://www.hcp.ma), the official demographic data is available for 1994, 2004, and 2014, the evolution of the population and its concentration in different areas has been tracked to compare the areas affected by deforestation with the most populated zones in order to assess the impact of human population on vegetation. For the years without available data, the population is estimated using the geometric rate model: Pn = P0 x (1+r)^t (United Nations [UN], 2016), where P0 is the population at the beginning of the period, t is the period of time in years, r is the annual rate of increase, and Pn is the estimated population at the end of the period. This approach permits the comprehension of the changes in population and their potential correlation with vegetation changes in the study area.

2.7. Vegetation area calculation

The Landsat remote sensing data is utilized, with a spatial resolution of approximately 30 meters. The red and infrared bands is also used to establish NDVI (Normalized Difference Vegetation Index) results.

To ensure high-quality results, the chosen season for this study is summer, specifically the month of August, as it is expected to have minimal effects from agriculture and grasslands, allowing for a clearer representation of natural vegetation, since, during the summer, the herbaceous vegetation degenerates, and the crops are harvested. Therefore, only natural vegetation persists. The methodology adopted in this work involves locating and identifying different types of vegetation formations (sparse, medium, and dense) on the ground and Google Earth archives with ArcGIS to determine the recovery rate as reported in table 1, then mapping them across the entire geopark using supervised classification based on shapefiles of these vegetation classes for the years where Google Earth archives are available (between 2008 and 2021) NDVI values will be determined in a subsequent phase to establish the appropriate NDVI intervals for each vegetation class (as shown in Table 2); This stage is resorted to because the image data required for supervised classification are not available. The same NDVI intervals were then applied over the remaining study period (1984-2007) using NDVI data to deduce the fluctuations in each vegetation class area. All these processes are performed using ArcGIS and Google Earth Engine environment.

Table 1. Calculation of recovery rates

Recovery rates	Cover nature
0%	bare soils
>30%	low density vegetation
<70% and >30%	medium density vegetation
>70%	high density vegetation

Own elaboration

2.8. Statistical study of the dataset

The evolution of vegetation is undoubtedly influenced by various environmental factors, including those associated with human land use in the area. While pairwise correlations between variables are important, it is also necessary to study all variables collectively to establish cause-and-effect relationships. This holistic approach is crucial in understanding how different factors interplay and shape the dynamics of vegetation in the study area, including both environmental and anthropogenic influences. Therefore, Principal Component Analysis (PCA) will be used to set the importance of each variable in each vegetation class. The basic aim of the analysis utilizing principal components is a reduction of the dimensions of the observation space in which given objects are studied (Maćkiewicz & Ratajczak, 1993). PCA is a method used to reduce the dimensionality of datasets, making them more interpretable, while striving to minimize the loss of information (Jolliffe & Cadima, 2016). FactorMineR package is used for running PCA analysis.

3. Results

3.1. The vegetation area during the month of August from 1984 to 2021

Vegetation density directly affects NDVI values; degraded forest, herbaceous, or grassland vegetation generally yields relatively low NDVI values, values produced by medium-density vegetation are typically moderate, and high-density vegetation reflects higher values. In addition, the vegetation cover presents a large-scale fluctuation (Figure 2 and 3 and table 3); the vegetation classes tend to decrease, with a different magnitude; the sparse, medium, and dense covers, lost respectively 0.02%, 29.5%, and 70.9%.

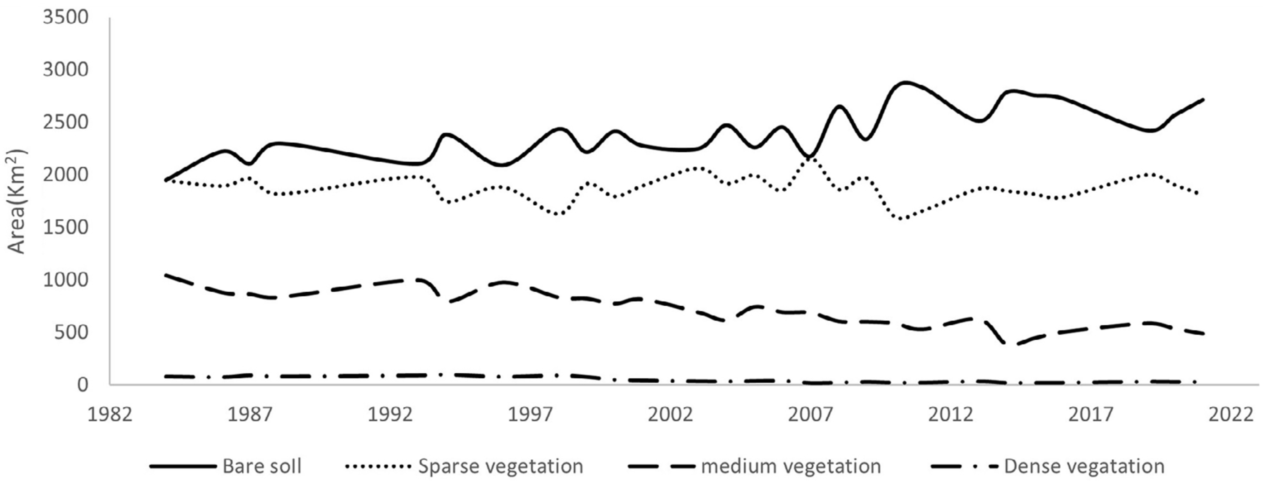
Table 2. the variation of NDVI classes according to vegetation cover classes

	NDVI range for Landsat 5	NDVI range for Landsat 8
Baren soils (+water)	Minimal value* -0.04	Minimal values* -0.1
Low density cover	0.04-0.14	0.1-0.165
Medium density cover	0.14-0.32	0.165-0.28
High density cover	0.32- maximal value	0.28- maximal values

*The choose of the minimum value is justified by the absence of the water areas

Own elaboration

Figure 2. the vegetation cover fluctuations during August between 1984 and 2021



Own elaboration

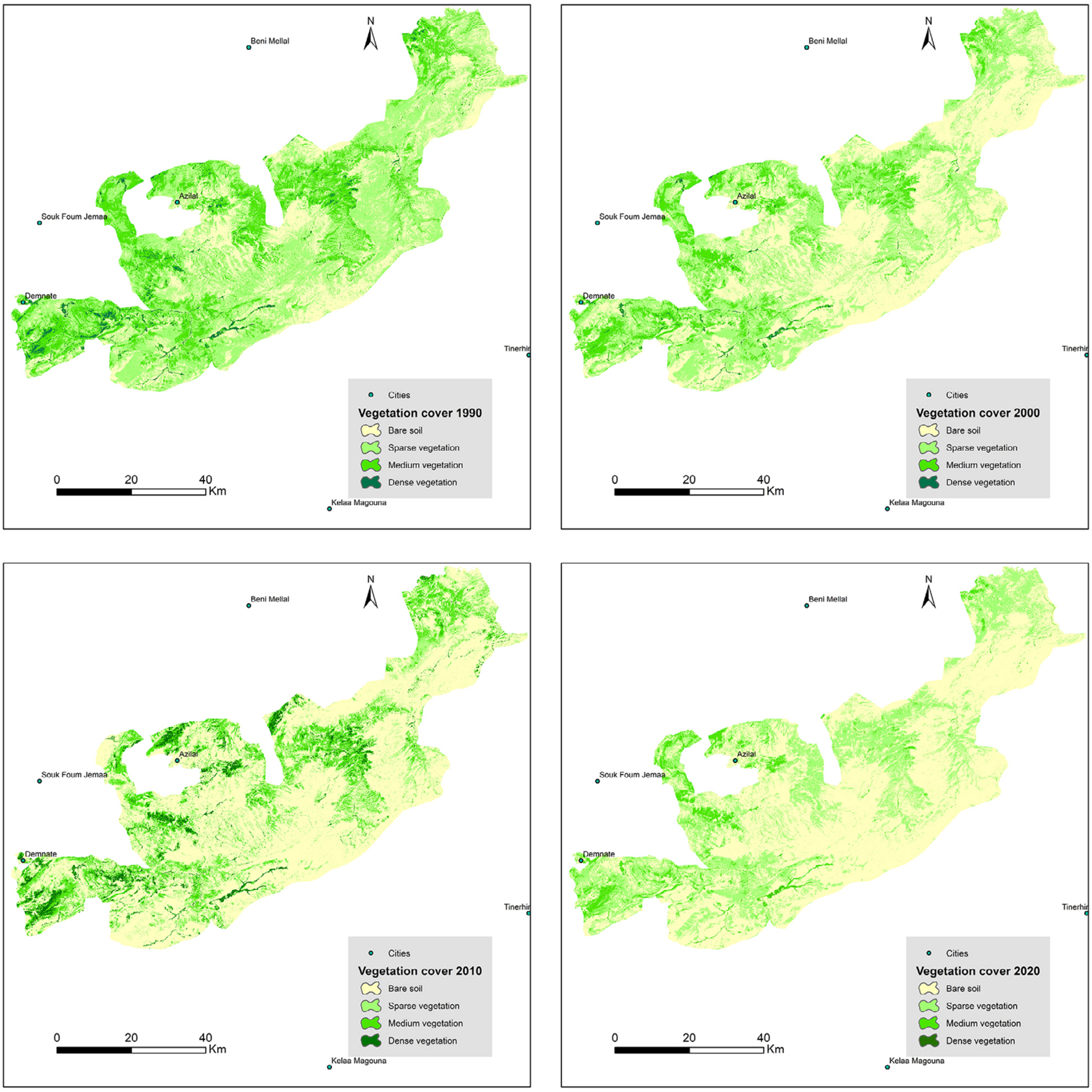
Table 3. The vegetation cover fluctuations (km^2)*

Soil cover	Bare soil	Low vegetation cover	Medium cover	Dense cover
Min value (year)	1,953 (1984)	1,604.168 (2010)	444.5 (2015)	16.08 (2007)
Max value (year)	2,830.305 (2011)	2,157.079 (2007)	1,043.43 (1984)	99.85 (1994)
fluctuations	+528 km^2	-49 km^2	-295.34	-70.2 km^2

*These fluctuations are deduced from the linear regression of each parameter

Own elaboration

Figure 3. The vegetation dynamic maps in a) 1990, b) 2000, c) 2010, and c) 2020



Own elaboration

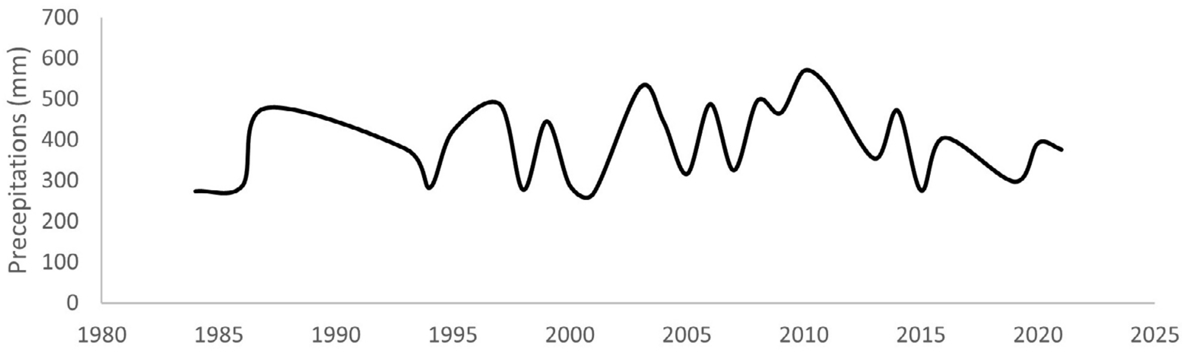
3.2. Climate parameters

A slight increase in average annual precipitation and an increase in drought periods were recorded along the study period, however, precipitation became more erratic, as shown in Figures 4 and 5, with prolonged periods of drought.

The average annual precipitation varies within the M'goun Geopark both spatially and temporally. In 1990, the annual average maximum precipitation reached 457.26 mm, followed by 391.09 mm in 2000, 733.83 mm in 2010, and 507.23 mm in 2020. As for the annual average minimum precipitation, it was 266.33 mm in 1990, 247.13 mm in 2000, 426.46 mm in 2010, and 299.65 mm in 2020. Generally, precipitation levels are higher in the northern and western parts of the study area, gradually diminishing towards the south (Figure 5).

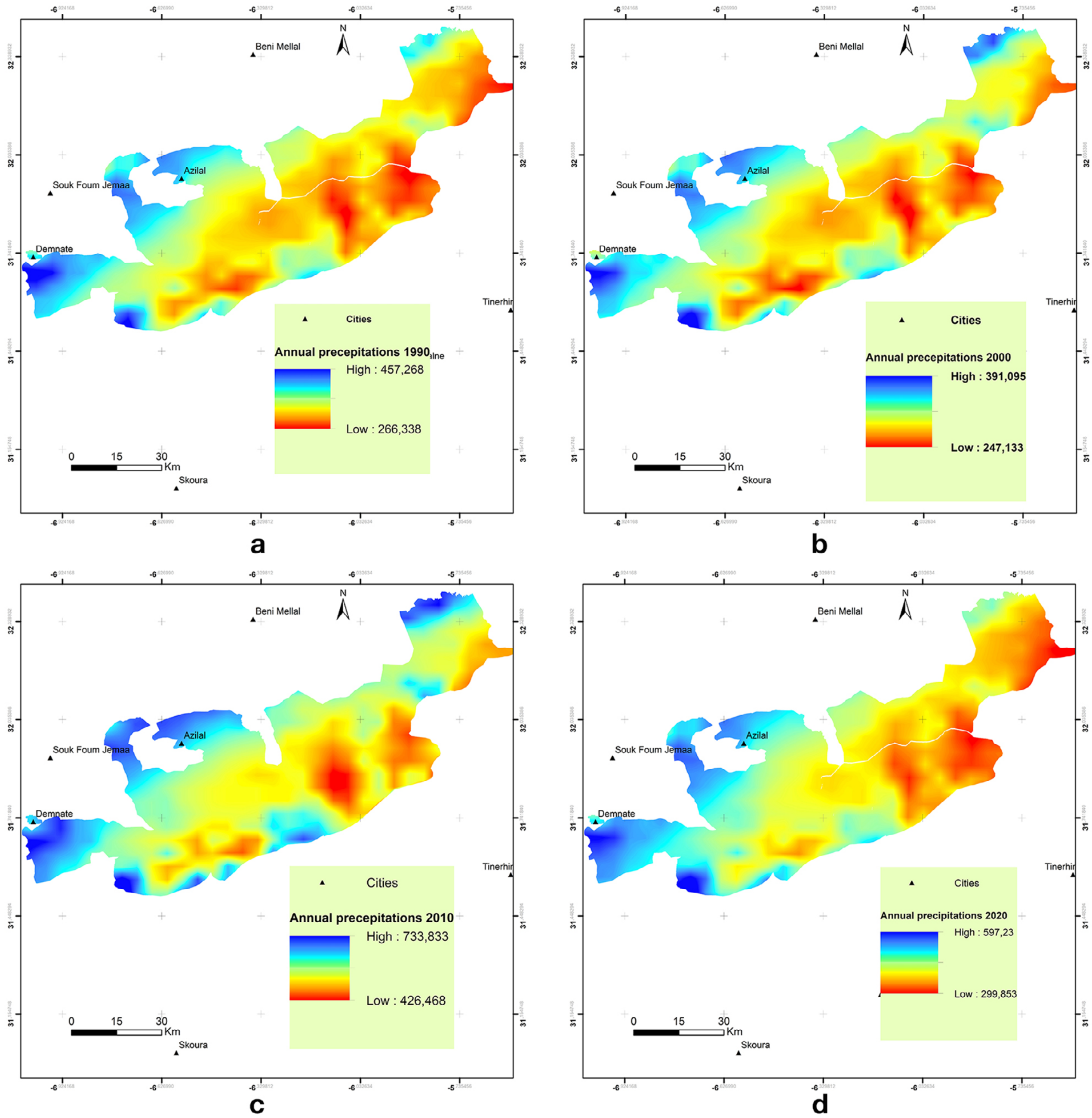
On the other hand, temperatures have been significantly increased, the average maximum temperatures from rose by 1.7 °C for the averaged value of the four selected locations. The average minimum temperatures from increase by 1.4 °C during the same period (Figure 6 and Table 4).

Figure 4. The variation of annual precipitation of the selected stations between 1984 and 2021



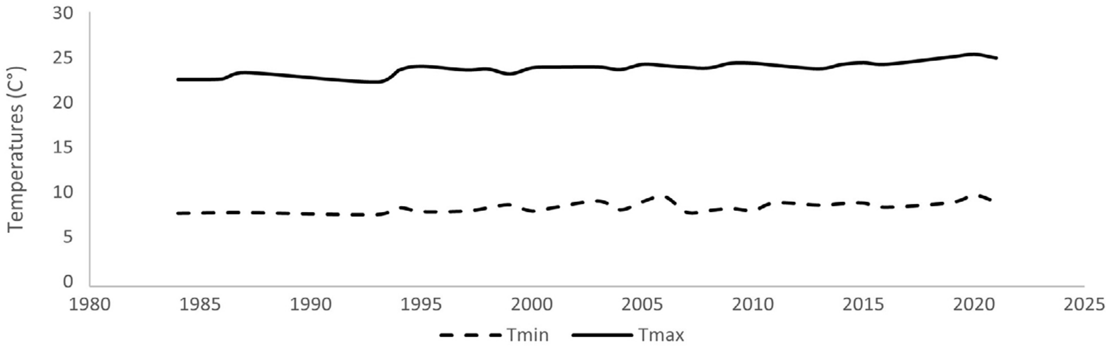
Own elaboration

Figure 5. The variation in average annual precipitations in a) 1990, b) 2000, c) 2010, and d) 2020



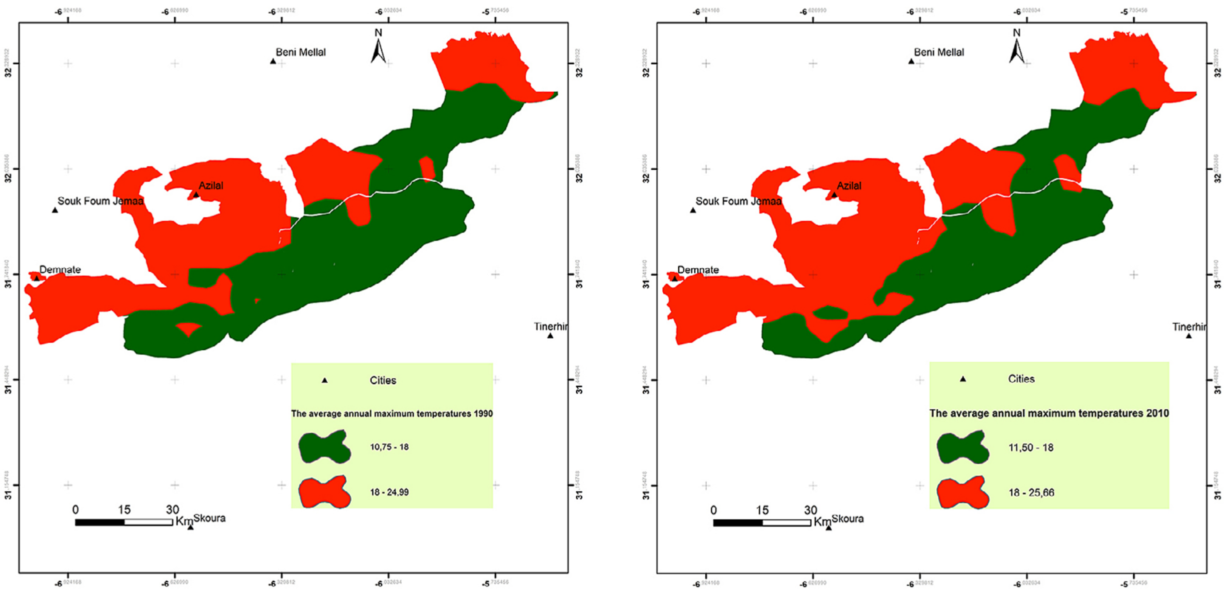
Own elaboration

Figure 6. The average annual of maximal and minimal temperatures of the selected stations between 1984 and 2021



Own elaboration

Figure 7. The average maximum temperatures variation in a) 1990 and b) 2010

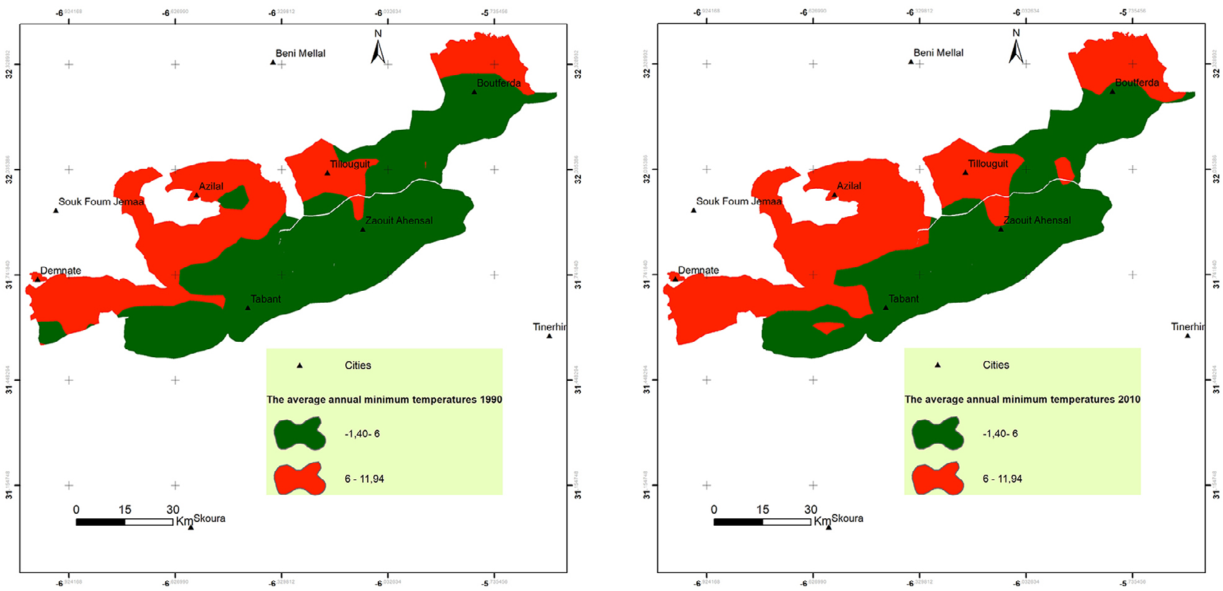


a

b

Own elaboration

Figure 8. The average minimum temperatures variation in a) 1990 and b) 2010



a

b

Own elaboration

The variation in average maximum temperatures reveals continuous climatic warming. Figures 7 and 8 demonstrate an increase in the area occupied by average maximum temperatures exceeding 18°C in 1990 compared to 2010, as well as the same trend for average minimum temperatures.

Table 4. the climate parameters fluctuations

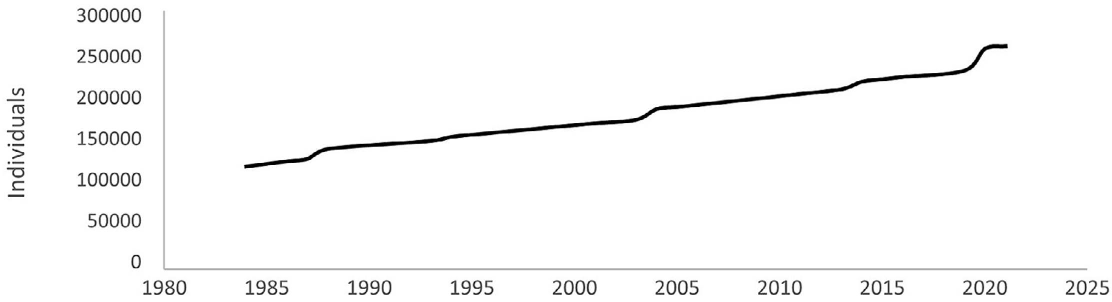
Climatic parameter	Tmax	Tmin	Precipitation
Max value	25.35 (2020)	9.98 (2020)	570.225 (2010)
Min value	22.32 (1993)	7.57 (1992)	268.325 (2001)
Fluctuations	+1.7 °C	+1.4 °C	+20 mm

Own elaboration

3.3. Demographic data

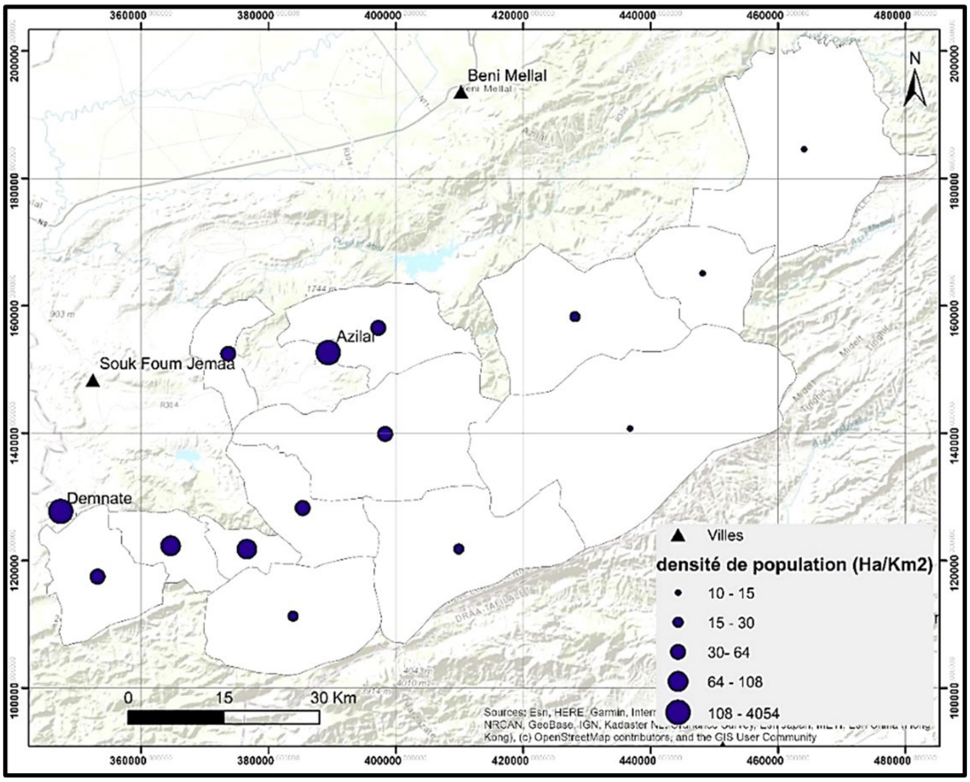
The population has grown considerably between 1984 and 2021 (Figure 9), the population rate in 1984 is 119307.88 people and 220 086.61 people in 2021. Therefore, the population inside the geopark M'goun has increased by at least 100 779 people between 1984 and 2021, which means an increase of 84.47%. The demography density map reveals that a high population density is present in the northern regions (Figure 10).

Figure 9. the population evolution between 1984 and 2021



Own elaboration

Figure 10. The population density map within M'goun Geopark

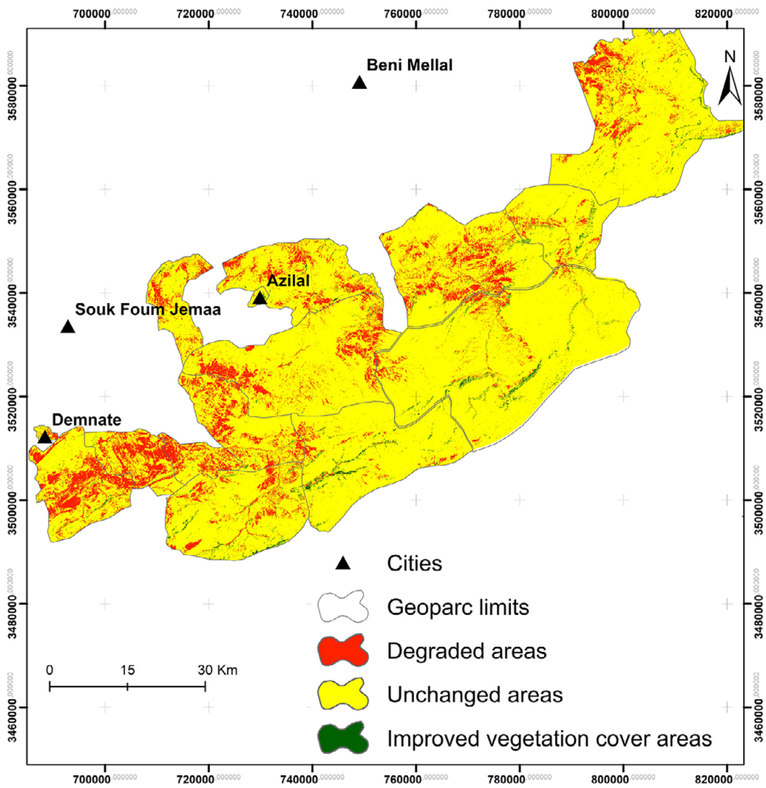


Own elaboration

3.4. The vegetation change detection map

While the southern areas of the geopark are seeing some growth in vegetation cover due to reforestation, the northern regions are mainly affected by the degradation of vegetation cover (Figure 11). Bare soils increased from 1953.00 km² in 1984 to 2714.83 km² in 2021, while sparse vegetation decreased from 1947.96 km² in 1984 to 1810.624 km² in 2021. The medium vegetation cover declined from 1043.43 km² in 1984 to 486.927 km² in 2021, and the dense vegetation cover decreased from 80.12 km² in 1984 to 25.6518 km² in 2021 (Table 5).

Figure 11. The change detection map result 1984 and 2021



Own elaboration

Table 5. The variation of Land occupation in the Geopark M'goun between 1984 and 2021

	Bare soil	Sparse vegetation	Medium vegetation	Dense vegatation
1984	1953.00	1947.96	1043.43	80.12
2021	2714.83	1810.624	486.927	25.6518

Own elaboration

3.5. The correlation climate-vegetation and population-vegetation

Pairwise correlations (Table 6) between variables show that medium cover is negatively correlated with Tmin and strongly correlated with Tmax and population. Similarly, dense cover is negatively correlated with Tmax and population.

Table 6. Correlation between vegetation cover and climatic variables with vegetation and population

	Low cover	Medium cover	Dense cover
Tmax (p-value)	ns*	-0.70 (3.634e-05)	-0.64 (0.00032)
Tmin (p-value)	ns*	-0.52(0.0046)	ns*
Precipitation (p-value)	ns*	ns*	ns*
Population (p-value)	ns*	-0.87 (1.828e-09)	-0.80 (3.784e-07)

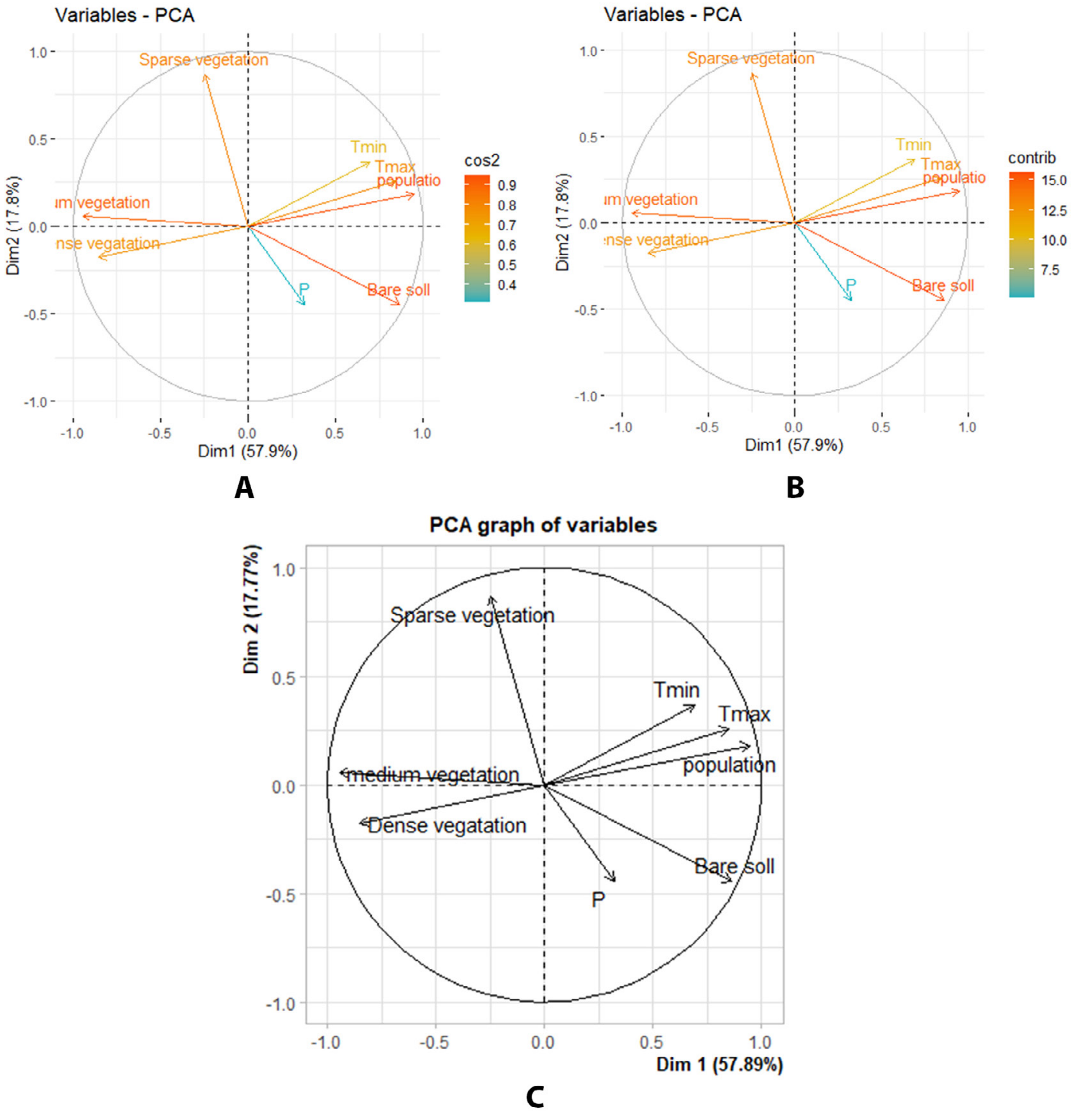
*Not significant

Own elaboration

3.6. PCA outputs

The variance explained by CP1 is 57.89%, CP2 represents 17.77%, and CP3 shows 10.8%. As a result, they together capture an accumulated explained variance of 85.66%, which represents the most important variability of the data (Figure 12). We observe that temperatures (Tmin and Tmax) and Population are grouped along the positive PC1, while medium and dense vegetation are pointed towards the negative side of CP1. Sparse vegetation is separated from other vegetation classes. Bare soil is represented in positive PC1 and negative PC2. Precipitation (P) is represented in PC3 and contributes 75% to its total variance. Population, sparse vegetation, medium vegetation, and bare soil are the variables that contribute the most to CP1 and CP2, followed by Tmax, Tmin, and dense vegetation, while precipitation has the lowest contribution to the first two principal components. The test of significance, Cos2, follows the same trend. When individuals are closer, they are more similar, with lower numbers representing the beginning of the study period and higher numbers reflecting the last year of the study period.

Figure 12. The CPA analysis results : A) the variables contibutions in the CP1 and 2; B) CPA plot of the reperesentation quality C) CPA plot of variables



Own elaboration

4. Discussion

The area occupied by bare soil tends to increase, indicating the degradation of vegetation surfaces inside the study area. Regarding the low-density cover, it is relatively stable (with a slight decrease of 49 km^2). This relative stability results from the medium- and high-density covers degrading into the low-density cover. The medium cover has large fluctuations and tends to decline, losing an average of 295 km^2. As for the dense vegetation cover, it lost 70.2 km^2 of its total area. In general, the vegetation cover has experienced significant fluctuations, on average, the rate of low-density vegetation has slightly decreased by 0.02%, while the rates of medium and high-density vegetation have decreased by 29.5% and 70.9% respectively, similar study conducted by Houssni et al. (2018) showed that high formations, low formations, and matorrals have regressed by 62%, 70%, and 49% respectively in the Western Rif region of Morocco (Houssni et al., 2018).

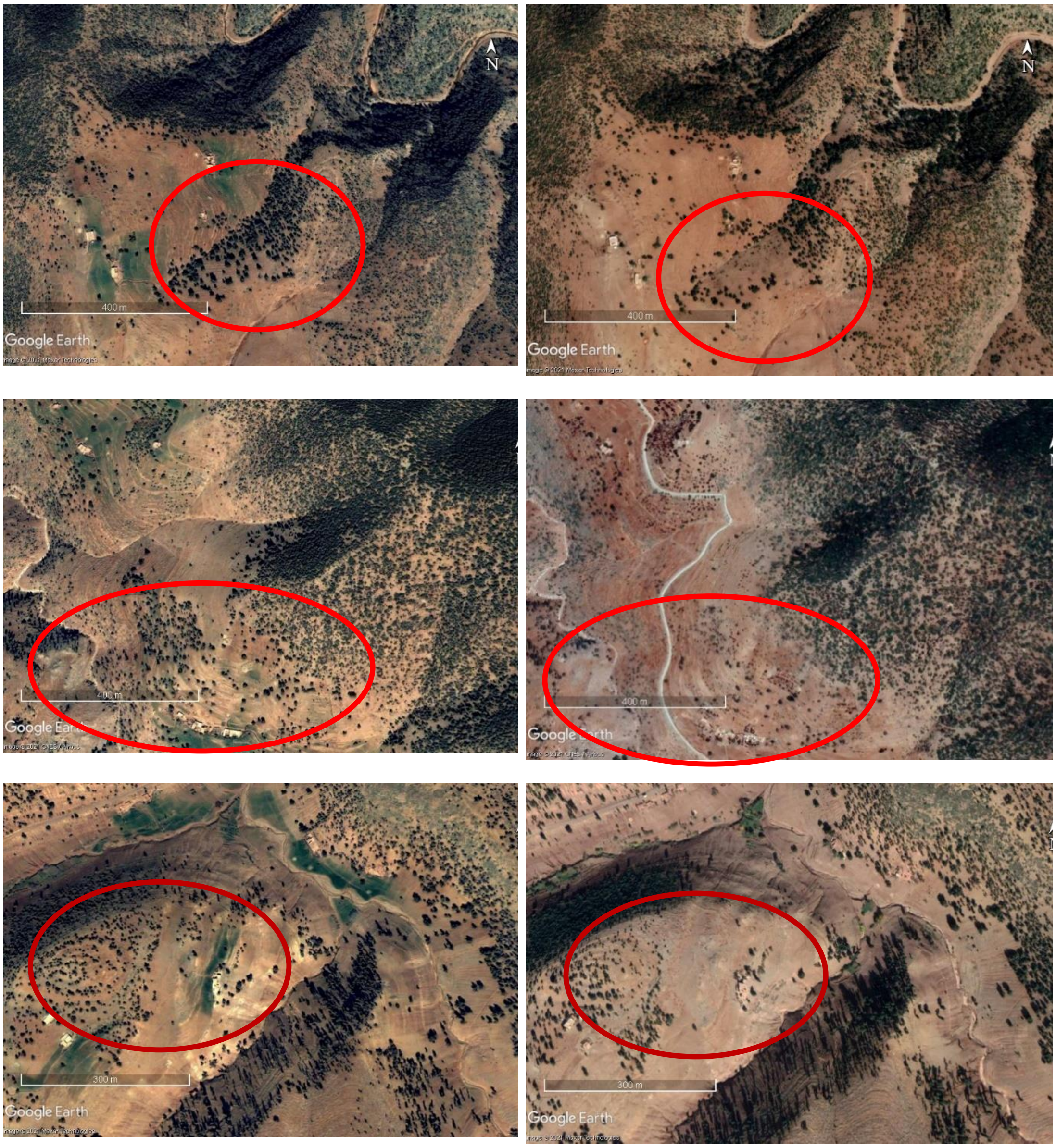
The average annual precipitation rate has slightly increased during the studied period by 20 mm, Bell et al. have underlined the precipitation understanding complexity in the High Atlas region of Morocco showing that the mean annual precipitation increases by 166 mm.km−1 (150.6 to 183.7 mm km−1) with a significant snow component at the highest elevations (Bell et al., 2022). However, in the last few decades, there have been long periods of drought, irregularities in rainfall (Ouharba et al., 2019), and records of both maximum and minimum temperatures, as significant warming trend has been observed, with maximum and minimum temperatures rising by 1.7°C and 1.4°C, respectively, during the study period. The same results are emphasized by Ait El-Mokhtar et al., who consider Morocco one of the most affected ecosystems by climate changes, especially drought, which deteriorates natural resources (Ait-el-mokhtar et al., 2019). This has resulted in the degradation of plants and must reduce the renewal vegetation rates. Furthermore, a study connects significant socioeconomic and agricultural advancements in North Africa to the environmental effects of climate change showed that, by 2050, rainfall in North Africa is projected to fall by 10–20% while temperatures are projected to climb by 2–3°C (Schilling et al., 2012). In addition The Land Surface Temperatures had significantly increased overall from 1984 to 2017, as it moved from a mean value of 29.4° C in 1984 to 40.4° C in 2007 and then reduced slightly to 37.9° C in 2017 (Khalis et al., 2021). Moreover, the majority of precipitation events have become stormier, which has resulted in significant erosion instead of promoting vegetation cover. Therefore, as a results of the drought episodes, in Oued Lahdar in Northeastern fully vegetated areas represented 94.3% in 1984 before deteriorating to 35.4% in 2007 (after an acute drought episode) and recovering in 2017 to 54.3%. While bare soil, which previously constituted 5.7%, reached a very high value of 64.6% in 2007 and then decreased to 47.7% (Khalis et al., 2021).

The fluctuations in vegetation during summer are slightly dependent on precipitation ($r = 0.24, 0.31, 0.23$, respectively, for sparse, medium, and dense cover). This can be attributed to irregularities in precipitation and the presence of other major variables that influence vegetation cover in the area. Moreover, fluctuations in medium and dense cover are strongly correlated with maximal temperatures ($r = -0.70$, $p = 3.634e-05$ for medium cover, and $r = -0.64$, $p = 0.00032$ for dense cover). Furthermore, medium cover is moderately correlated with minimal temperatures ($r = -0.52$, $p = 0.0046$). Therefore, rising temperatures are the primary climate parameter that significantly affects vegetation cover, as Morocco has witnessed unprecedented records of heat waves (Brimicombe et al., 2021). Furthermore, Akensous et al. have followed the same process, as well as this current study, in a nearby Tansift region, and have demonstrate that the temperature and vegetation cover shows a low regression coefficient value of 0.3057 and, rainfall and vegetation cover analysis show regression coefficient value of 0.7024 (Akensous et al., 2021), these differences may be explained by the dissimilarities between the two study areas. While Tansif experiences a pre-desert severe arid climate, with plants adapted to high temperature degrees, the Geopark M'goun is situated in a subhumid climate zone (Gharnit et al., 2023).

Additionally, the correlation shows an important dependence between medium cover ($r = 0.87$, $p=1.828e-09$), dense cover ($r = 0.8$, $p=3.784e-07$), and population. Moreover, comparing the population growth between the years 1984 and 2021 reveals a massive increase and a sudden demographic explosion, with the population increasing from 119,307 people to 220,086 people, an increase of 84.47%. Consequently, the impact on natural resources has been exacerbated by population growth and its needs. This important increase in the population rate profoundly affects the vegetation, as Muller et al. have studied the History of Moroccan vegetation especially in the north near to Spain showing surprising lack of human impact during the late Neolithic, little impact during Roman colonization, and anthropogenic activities however have led to severe modification during the last centuries as the understory structure of these forests are on-going deforestation that presently threatens this invaluable biological heritage (Muller et al., 2015). As a result, the major factor the shape the vegetation cover dynamism in the Atlas region of Morocco is population.

The PCA reveals that climatic and anthropogenic factors have strongly affected the vegetation evolution in the study area. It demonstrates that population, Tmin, and Tmax have a profound effect on the dense and medium cover. However, precipitation appears to have less of an effect. In contrast, the difference in the tendency of vegetation classes (dense, medium and sparse) and bare soil is an index of the desertification, in other words, the transformation of the vegetation area into the bare soils, as 93% of the Moroccan territory is affected by the phenomenon of desertification (Labbaci & Ouchaou, 2021). The relative lack of correlation between low vegetation cover density and climatic or anthropic factors may be attributed to the heterogeneity of this vegetation class. The transformation of degraded dense vegetation into sparse cover, along with the presence of dwarf palms and other signs of deterioration, replacing dominant forest species such as holm oak, juniper and thuja and contribute to this variability. Additionally, summer rainfall (Khomsi et al., 2015), despite occurring during the month of August when herbaceous vegetation is typically degraded, can still result in stormy showers or late rainfall that further affects the composition of the vegetation cover. This variability underscores the complex nature of the Atlas climate and its influence on the dynamics of this vegetation class in particular and generally the vegetation cover.

Figure 13. a) Google Earth images taken from the northern part of the geopark for the year 2008 and b) Google Earth image of the same area for the year 2020



a b

Own elaboration

Vegetation degradation in the region can be attributed to several factors, including natural tree mortality caused by climate warming, irregular precipitation patterns, and aging plants (Dallahi et al., 2023). Additionally, deforestation for wood and charcoal, soil erosion and depletion, pollution, and the widespread use of wood for building new houses due to a lack of infrastructure for accessing modern construction materials. Moreover, one of the greatest causes of deforestation in the region is overgrazing, as the local population heavily relies on extensive cattle breeding and arboriculture as their primary source of income, the same findings are discussed by Culmsee (Culmsee, 2019). Furthermore, during the plowing season, farmers clear large areas of wild vegetation in search of new agricultural fields, leading to deforestation. Fekri Benbrahim et al. showed that the increase in agricultural land due to population growth and the expansion of export crops or livestock farming leads to deforestation and overgrazing, which promote water and wind erosion in Morocco (Benbrahim et al., 2004).

The change detection map (Figure 11) illustrates that the northern part of the geopark is particularly vulnerable to deforestation. Furthermore, the demographic density map (Figure 10) indicates that the most affected areas are characterized by high population density. Medium and dense vegetation persist in protected locations, away from human settlements and along the banks of the wadis where vegetation cover renewal is important. This deficit in vegetation cover can be observed in the field (Figure 13).

The images above provide evidence of a degradation in vegetation cover, highlighting the precarious and concerning situation of local ecosystems. The images from 2020 depict degraded and deficient vegetation cover compared to those from 2008, which is consistent with the evolutionary trend of vegetation cover deduced from remote sensing methods. These images, showing also the population's habitats, were selected from the most affected areas as identified in the change detection map. Despite the relatively short period between 2008 and 2021 compared to our study period, the vegetation cover has undergone significant fluctuation. Using the change detection technique in the northwestern region of Central Morocco confirms a decline in plant cover between 1990 and 2010, followed by an increase between 2010 and 2015, and then followed by another decline in these areas between 2015 and 2018 (Lahcen et al., 2022).

The vegetation dynamic and fundings of the current study generally support the same trends as the Mediterranean regions, as Mazzoleni et al. have emphasized the major effect of human activities on vegetation in the Mediterranean basin (Mazzoleni et al., 2005) and it is noteworthy that all warming scenarios in the Mediterranean predict an increase of drought and heat events, and a reduction in precipitation (Solomou et al., 2017). Furthermore, this forest deterioration is likely to worsen the erosion of biodiversity, which constitutes one of the most significant threats affecting Mediterranean ecosystems (Underwood et al., 2009).

5. Conclusions

The vegetation cover in the High Atlas of Morocco, in general, and the M'goun Geopark, in particular, is undergoing significant changes. There is a noticeable desertification of vegetation cover, which is being replaced by lower-quality vegetation and bare lands. This degradation is attributed to a combination of factors, including climate change resulting in reduced rainfall and increasing temperatures over time. Anthropogenic factors, such as tree cutting for charcoal, wood, and firewood, along with overgrazing and forest clearing for agriculture driven by population growth and a lifestyle centered on livestock and agriculture have impacted profoundly the vegetation cover. Change detection confirms that the areas most affected by degradation, with decreased vegetation density, are located in the northern part of the geopark, where population density is important.

The current findings help us understand the evolution of vegetation cover in the High Atlas and Morocco over space and time. They also highlight the most influential factors controlling this evolution, revealing the M'goun Geopark as a fragile ecosystem. Furthermore, these findings underscore the necessity of collaboration among all stakeholders to protect the remaining vegetation and implement reforestation projects.

The study area, being part of the Mediterranean region, exhibits similar trends to the entire Mediterranean basin, which is experiencing unprecedented desertification and increasingly severe climate conditions marked by rising temperatures and overall changes in precipitation patterns. Additionally, the Geopark is situated within the Atlas Mountain range, sharing similar characteristics, thus potentially allowing for the generalization of these results to the wider Moroccan Atlas region, where vegetation cover is also under threat.

In Morocco, many regions lack detailed vegetation studies. Therefore, further research should be conducted to assess the situation in each region, make informed decisions to protect and monitor this natural treasure, implement conservation policies, and understand the long-term impact of vegetation cover.

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